Planetary Science Institute

September 22, 2004

Dr. R. Stephen Saunders
Solar System Exploration Division
Code SE
Washington, D. C. 20046

Re: Planetary Geology and Geophysics Program Final Report

Dear Dr. Saunders:

As requested by NASA Headquarters, I am submitting this letter and the enclosed attachments as a final administrative report in the research program entitled "Collisional and Dynamical Evolution of Planetary Systems," Grant Number NAG5-13460, on which I was the Principal Investigator. This report covers the period May 1, 2003 - April 30, 2004. During this time, this research program produced the publications listed below:

"Jumping Jupiters" in binary star systems. F. Marzari, S. J. Weidenschilling, M. Barbieri and V. Granata. Astrophys. J., in press, 2005.

Formation of the cores of the outer planets. To appear in "The Outer Planets" (R. Kallenbach, ED), ISSI Conference Proceedings (Space Sci. Rev.), in press, 2005.

Accretion dynamics and timescales: Relation to chondrites. S. J. Weidenschilling and J. Cuzzi. In Meteorites and the Early Solar System II (D. Lauretta et al., Eds.), Univ. of Arizona Press, 2005.

Asteroidal heating and thermal stratification of the asteroid belt. A. Ghosh, S. J.Weidenschilling, H. Y. McSween, Jr. and A. Rubin. In Meteorites and the Early Solar System II (D. Lauretta et al., Eds.), Univ. of Arizona Press, 2005.

Abstracts of these publications are attached. I hope that this will satisfy the reporting requirements. Please feel free to contact me if you require any additional information.

Sincerely,

Stuart Weidenschilling

S. J. Weidenschilling
Senior Scientist

pc: Mrs. Janet Whitener
Mrs. Kelly Yoder

SEP 23 2004

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Jumping Jupiters in binary star systems

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ABSTRACT

We investigate the outcomes of the dynamical interaction of Jupiter–mass planets orbiting the central star in a binary system. These systems are unstable and lead to the hyperbolic ejection of one or more planets while the surviving bodies are inserted in inner eccentric orbits. The gravitational perturbations of the companion star, set at an intermediate distance (50 AU) and typically on an eccentric orbit, influence both the development of instability and the outcome of the subsequent chaotic evolution. We compute the statistical properties of the resulting planetary systems when they reach a stable configuration. The binary eccentricity and the number of initial planets (two or three) are strong predictors

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of the final configuration of the planetary system. Cases of apsidal resonance between two final planets, Kozai resonance between a single surviving planet and the companion star, and retrograde orbits with respect to the binary orbit are naturally produced.

Subject headings: stars: planetary systems – planetary systems: formation

1. Introduction

According to Jahreiss & Wielen (2000), the relative frequency of binary stars within 5 pc from the sun is roughly 50%. Surveys in the Tau–Aur association (Simon et al. 1992; Ghez et al. 1993; Leinert et al. 1993; Richichi et al. 1994) yield a similar frequency. Planetary formation in binary star systems is then a crucial process to estimate the overall frequency and dynamical properties of planets. Our current paradigm for planetary formation is that planets grow from dusty disks, remnants of star formation. In recent years, several investigations pointed out that disks are common in binary systems as for single stars (see Mathieu et al. (2000) for a review). A dusty gaseous disk approximately 200 AU in diameter has been imaged around the primary star of the binary system HR 4796A (Jayawardhana et al. 1998). A large hole in the center of the disk may be an indication of ongoing planetary formation. Interferometric images of L1551 IRS5 (Rodriguez el al. 1998) revealed that each star of this binary system is surrounded by an optically thick disk. Although the disks in binary systems may be reduced in size by the presence of the companion star, the circumstellar disk material may be similar in temperature and surface density to that of disks around single stars. As a consequence, planetary formation may proceed and the spatial distance and final mass of the planets would be determined by the properties of the gas and dust.

At present, 19 extrasolar planets are known within 15 binary systems (http://cfa-www.harvard.edu/planets/). In all of these cases, the planets orbit one of the stars, with the companion star in a more distant orbit. The closest binary system currently known to have a planet is Gamma Cephei, with separation 18 AU and eccentricity 0.36 (Hatzes et al. 2003). Recently, two additional binary systems with similar separation, Gl 86 (Eggenberger 2004) and HD 41004 (Santos et al. 2002), have been found to have planets. Detection of planets by radial velocity surveys is more difficult for close binary systems, due to the light of the companion star and blending of spectral lines; it is not yet clear whether their abundance is similar for single and binary stars. Assuming that planets can form in binary systems with similar properties as around single stars, it is important to understand how the presence of a companion star affects their dynamical evolution. In earlier papers (Weidenschilling & Marzari 1996; Marzari & Weidenschilling 2002), we proposed that observed peculiarities of

FORMATION OF THE CORES OF THE OUTER PLANETS

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Received: 29 June 2004; Accepted in final form: xx September 2004

Abstract. The formation of the giant planets seems to be best explained by accretion of planetesimals to form massive cores, which in the case of Jupiter and Saturn were able to capture nebular gas. However, the timescale for accretion of such cores has been a problem. Accretion in the outer solar system differs qualitatively from planetary growth in the terrestrial region, as the larger embryo masses and lower orbital velocities make bodies more subject to gravitational scattering. The planetesimal swarm in the outer nebula may be seeded by earlier-formed large bodies scattered from the region near the nebular "snow line." Such a seed body can experience rapid runaway growth undisturbed by competitors; the style of growth is not oligarchy, but monarchy.

Keywords: Accretion, giant planets, planetesimals

1. Introduction

The four giant planets are naturally classified into two groups: the gas giants Jupiter and Saturn, and the ice giants Uranus and Neptune. The gas giants consist mostly of hydrogen and helium, yet these planets are significantly enriched in heavier elements (metal, silicates, and ices) by about an order of magnitude relative to solar composition. For Jupiter, uncertainties in the equation of state of hydrogen allow ambiguity in the location of the heavy elements; they may be concentrated in a central core, or distributed throughout its interior. However, Saturn is required to have a core of about 10 $M_{\oplus}$ (Wuchterl *et al.*, 2000). Uranus and Neptune contain about 10% by mass of H and He, which is only a small fraction (< 1%) of their solar complement relative to their heavy elements. They may be regarded in some sense as "nearly naked cores."

The formation of these planets poses problems for theorists. The most widely accepted model for the formation of the gas giants is "core-accretion." In this scenario, planetesimals accreted by collisions, building up massive protoplanetary embryos. Such an embryo could capture a massive H-He atmosphere from the surrounding solar nebula. The mass of this atmosphere increased with the embryo (core) mass, and when the core attained a critical mass, estimated to be about $10 M_{\oplus}$, the gaseous envelope underwent a hydrodynamic collapse, capturing gas from the nebula until the supply near its orbit was exhausted. This description is rather simplified; for a more complete explanation see Pollack *et al.* (1996).

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Accretion Dynamics and Timescales: Relation to Chondrites

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NASA Ames Research Center

In this chapter we consider aspects of the formation of a presumed initial population of ~ km-sized planetesimals and their accretion to form larger bodies in the asteroid belt, including the parent bodies of meteorites. Emphasis is on timescales predicted from dynamical models and comparison with measured ages of meteoritic components. In the simplest models, the timescales for planetesimal formation and accretion of protoplanetary embryos are not consistent with the apparent age difference between CAIs and chondrules, the inferred duration for chondrule formation, or the expected degree of heating and metamorphism due to ^{26}Al. We suggest alternative scenarios that may delay planetesimal formation and/or produce chondrites from recycled debris of first-generation planetesimals that were collisionally disrupted after Jupiter formed. We discuss collisional evolution during and after accretion, and consequences for lithification of meteorites. The region of the solid nebula that corresponded to the asteroid belt originally contained ~ 10^3 times its present mass of solar matter. The present asteroid belt does not represent an unbiased sample of that material. Meteorites are preferentially derived from bodies originally between a few tens and a few hundreds of km in size; these were sufficiently small and numerous to leave a remnant population after depletion of the belt, but large enough to survive the subsequent 4.5 Gy of collisional evolution.

1. INTRODUCTION

Collisions played a dominant role in the evolution of the parent bodies of meteorites, from their accretion as (more or less) "pristine" planetesimals, through the stirring and depletion of the asteroid belt and its collisional evolution over the subsequent ~ 4.5 Gy of solar system history. Elsewhere in this volume (*Cuzzi and Weidenschilling,* 2005), we discuss the earliest stage of "primary accretion," which occurred during the formation of planetesimals from small grains and particles that were controlled or influenced by the gas in the solar nebula. In the present chapter, we explore the later evolution of the swarm of planetesimals that presumably formed in the asteroid region. We begin by summarizing in Section 2 the "conventional wisdom" as of the previous volume in this series, *MESS I* (*Kerridge and Matthews,* 1988), and in Section 3 changes to that picture that have resulted from more recent work. We then examine in Section 4 the current models for planetesimal formation, accretion of protoplanetary embryos, removal of most of the primordial mass from the asteroid region, consolidation and lithification of asteroids, and the later collisional evolution of the remnant population. Simple models for planetesimal formation and embryo growth predict timescales for these processes that are not consistent with measured ages of CAIs and chondrules. In Section 5 we explore two possible scenarios for the

Asteroidal Heating and Thermal Stratification of the Asteroid Belt

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Abstract

The asteroid belt is thermally stratified, with melted or metamorphosed asteroids dominating the inner belt and relatively unaltered asteroids dominating the outer belt. The compositional structure of the asteroid belt is a unique signature of the heating agent that caused melting and metamorphism of planetesimals in the early solar nebula; thus, it constitutes an important test of plausibility of heating mechanisms. Previous work attributes the stratification to a radial thermal gradient in the solar nebula or heating by ^{26}Al decay or electromagnetic induction. Present thinking attributes the thermal stratification of multiple processes multiple processes that were active in the early Solar System, including ^{26}Al, the dependence of accretion timescale on heliocentric distance, the presence of ice in planetesimals that formed in the outer belt, and loss of primitive material by collisional disruption of small asteroids over the age of the solar system.

1. HEAT SOURCES IN THE EARLY SOLAR SYSTEM

Half a century ago, Harold Urey recognized that "it is difficult to believe that heating by K, U and Th is a feasible explanation for the high-temperature stage required to produce the meteorites." He proceeded to perform the first back of the envelope calculation and suggested

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